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# MK25 TORPEDO EXHAUST GAS INVESTIGATION

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THE HIGH SPEED WATER TUNNEL  
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PASADENA, CALIFORNIA

SECTION № 6.1-sr 207-1916  
HML № ND-30.4

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DIVISION SIX - SECTION 6.1

MK 25 TORPEDO  
EXHAUST GAS INVESTIGATION

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THE HIGH SPEED WATER TUNNEL  
AT THE  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
HYDRODYNAMICS LABORATORY  
PASADENA, CALIFORNIA

Section No. 6.1-sr207-1916

HML No. ND-30.4

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April 12, 1945

WATER TUNNEL TESTS  
OF THE  
MK 25 TORPEDO  
EXHAUST WITH PROPELLER  
AND SINGLE AND DOUBLE PIPES

GENERAL

This report covers tests made on models of the Mk 25 Torpedo to determine the effect of gas discharged in the vicinity of a power-driven propeller. It also covers, briefly, tests made on a double exhaust pipe and a single exhaust pipe, both with the vertical rudder set at  $40^{\circ}$  port but without propeller. All of the above was authorized by Dr. E. H. Colpitts, Chief of Section 6.4, NDRC, in a letter dated May 4, 1944. This report is the fourth supplement to the report, Section No. 6.4-sr207-1275. Memorandum Reports dated June 22, 1944, July 15, 1944, and September 29, 1944, have been issued giving preliminary results on the tests reported herein.

Tests were made on models having a scale ratio of 11.21. However, all dimensions and data refer to the prototype unless otherwise noted.

Gas discharges are expressed in per cent. These figures have been calculated with reference to the amount of gas discharged from the prototype when running at 40.5 knots. Allowances for temperature and composition of the exhaust gases have been made by calculating the exit velocity when the torpedo is running at 40.5 knots and 15 feet submergence, computing the ratio of this velocity to that of the torpedo, and then calculating the amount of air required by the model to obtain this velocity ratio when operating at the equivalent submergence. This criterion requires that a different rate of air flow be taken as the 100% amount for each torpedo velocity investigated. However, as in the prototype, the mass rate of gas flow in the model is constant for any given water velocity, independent of the changes in the tunnel pressure (i.e. submergence).

With this torpedo operating at the normal speed of 40.5 knots and a submergence of 15 feet, the cavitation parameter is calculated to be 0.67.

The appendix to this report gives definitions of terms and other pertinent data.

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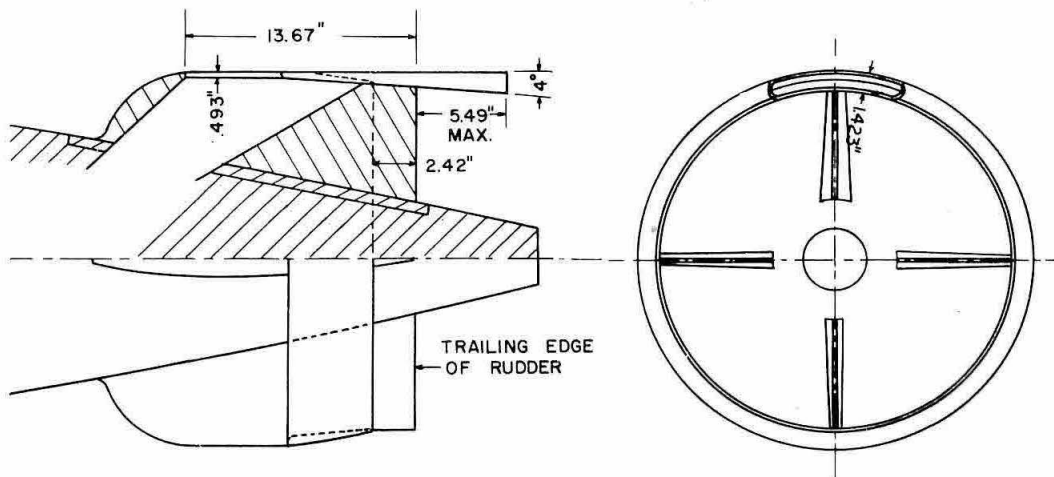


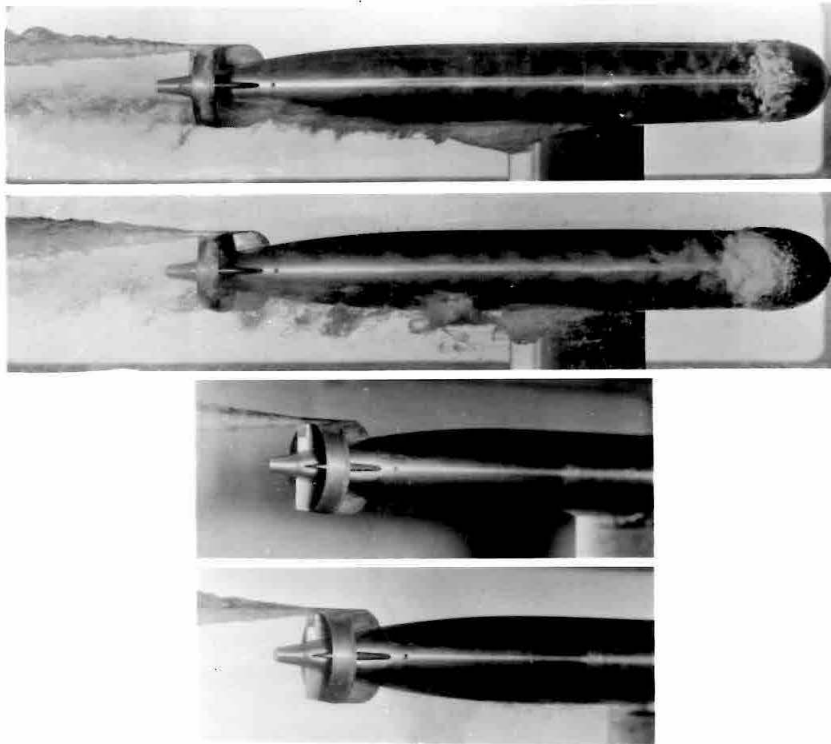
FIG. 1 DETAIL OF SINGLE EXPANDING EXHAUST PIPE

SINGLE EXPANDING EXHAUST PIPE WITHOUT PROPELLER

The second supplement to report Section No. 6.4-sr207-1275 (ND-30.2) covered an investigation of the exhaust through a single expanding pipe and with neutral rudders. Figure 1 is an outline drawing of the single expanding exhaust pipe. The object of this additional testing was to determine if the exhaust caused any interference with the rudder when the rudder was set at  $10^{\circ}$  port.

These tests were commenced with the full length of exhaust pipe (5.49" beyond trailing edge of rudder) and observations were made for values of the cavitation parameter,  $K$ , from 1.0 to 0.5 at  $0^{\circ}$  and  $+5^{\circ}$  yaw. In no case was there observed any spreading of the exhaust cavity, with 100% exhaust, until the exhaust pipe was cut off flush with the trailing edge of the rudder. With this short pipe the exhaust cavity spread a short distance along the shroud ring either side of the pipe and also about half way down the rudder. This condition occurred at a  $K$  of 0.71, 100% exhaust, and zero yaw. It would appear that this amount of spreading of the exhaust cavity along the rudder would be enough to interfere with rudder operation.

As a result of these tests, it appears that the shortest exhaust pipe that could be used without causing interference with the rudders is one extending not less than 0.75" aft of the trailing edge of the rudder. This should give satisfactory performance for yaw angles up to  $5^{\circ}$  and values of  $K$  as low as 0.50. It must be borne in mind that this is the case *without* propellers. The minimum length of pipe required to avoid interference with the propeller operating is discussed later.



(a)  
K = 0.50  
 $\psi = 0^\circ$   
PIPE = 0.75"

(b)  
K = 0.52  
 $\psi = +5^\circ$   
PIPE = 0.75"

(c)  
K = 0.71  
 $\psi = 0^\circ$   
PIPE = 0"

(d)  
K = 0.72  
 $\psi = +3^\circ$   
PIPE = 0"

NOTES: PIPE LENGTH IS MEASURED  
FROM TRAILING EDGE OF  
VERTICAL RUDDER.  
AIR BUBBLES ALONG BOTTOM  
OF MODEL ARE DUE TO A  
LEAK INSIDE THE SHIELD.

VERTICAL RUDDER SET AT  $10^\circ$  PORT  
GAS DISCHARGE 100 %

FIG. 2 EXHAUST FROM SINGLE EXHAUST PIPE

Figure 2 (a) and (b), are flash photographs of 100% exhaust from the pipe 0.75" long at yaw angles of  $0^\circ$  and  $5^\circ$ , and a K of approximately 0.50. It is seen that the exhaust cavity is very compact with no tendency to spread to the vicinity of the rudder. As stated above, this represents what appears to be the minimum length of pipe for satisfactory performance, disregarding for the present any complication caused by the propellers.

Photographs (c) and (d), Figure 2, show the performance with the pipe cut off flush with the trailing edge of the rudder. Although the value of K for these photographs is only 0.70, there appears to be a tendency for the exhaust cavity to spread along the shroud ring and down the rudder. This effect was much more apparent when observing the model in the tunnel.



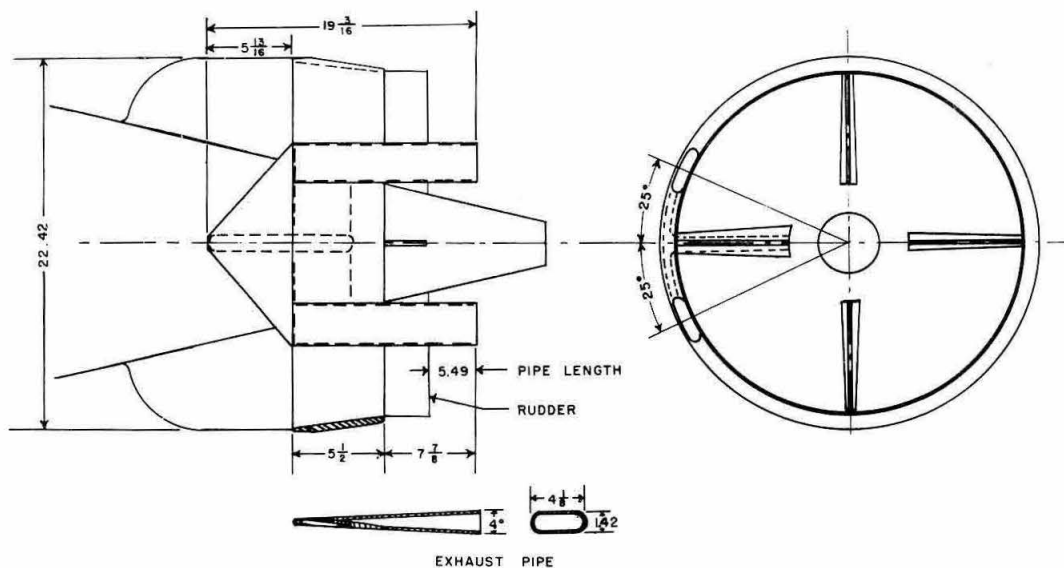
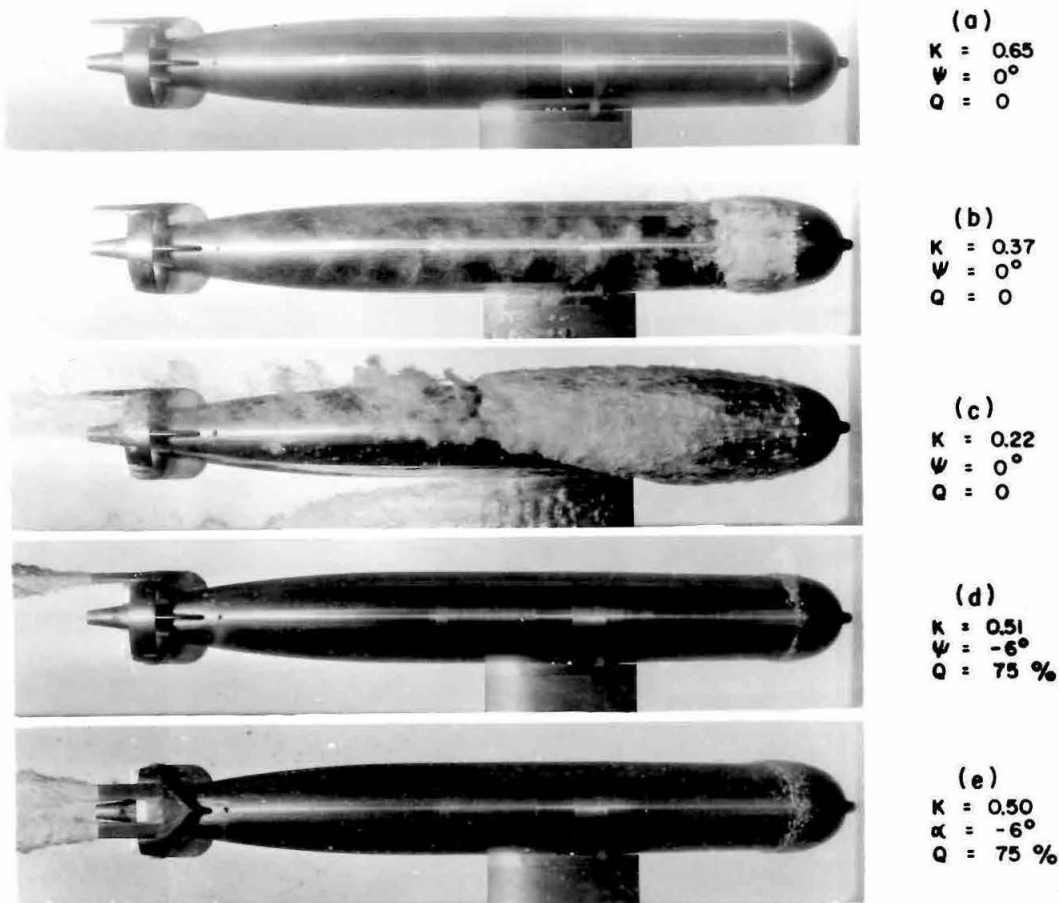


FIG. 3 DETAIL OF DOUBLE EXHAUST PIPE

DOUBLE EXHAUST PIPE

Figure 3 is an outline drawing of a double exhaust pipe designed to discharge the exhaust gases on both sides of the rudder in the expectation that this would avoid rudder interference.

These tests were commenced with the pipes extending 5.49" beyond the trailing edge of the vertical rudder and observations were also made for pipe lengths of 2.69", 0.75", and with the end flush with the rudder. In all of these runs, observations were made for values of K from 1.0 to 0.5, yaws of  $+6^\circ$  to  $-6^\circ$ , and pitch angles of  $+6^\circ$  to  $-6^\circ$ . The vertical rudder was set at  $10^\circ$  port and the exhaust gas was from 80% to 100% normal in all cases.



VERTICAL RUDDER SET AT  $10^\circ$  PORT  
 PIPE LENGTH, 5.49"  
 $Q = \text{GAS DISCHARGE}$

FIG. 4 DISCHARGE FROM DOUBLE EXHAUST PIPE

In Figure 4, photographs (a), (b), and (c) show the model with full length exhaust pipes and *no* exhaust gas. It is seen that no serious cavitation occurred on the ring until  $K$  was reduced to values below 0.37, although incipient cavitation occurred along the ring at a  $K$  of about 0.80.

Photographs (d) and (e), Figure 4, show the model with maximum length of exhaust pipes and discharging about 80% exhaust gas, the value of  $K$  being approximately 0.50. In (d), the model is operating with a yaw angle of  $-6^\circ$  and in (e), with a pitch angle of  $-6^\circ$ . No tendency for the exhaust cavity to spread to the ring or rudder was observed.

In Figure 5, photographs (a), (b), and (c) show the exhaust pipes extending 2.69" beyond the rudder, the exhaust being about 85% normal and  $K = 0.50$ . Photograph (a) is at  $-6^\circ$  yaw and photograph (c) at  $-6^\circ$  pitch, and in both of these cases no spreading of the exhaust cavity was observed which could interfere with the propeller or rudder action. Photograph (b) is included as a matter of interest as it shows how staggered bubbles are formed from the double exhaust under certain conditions.

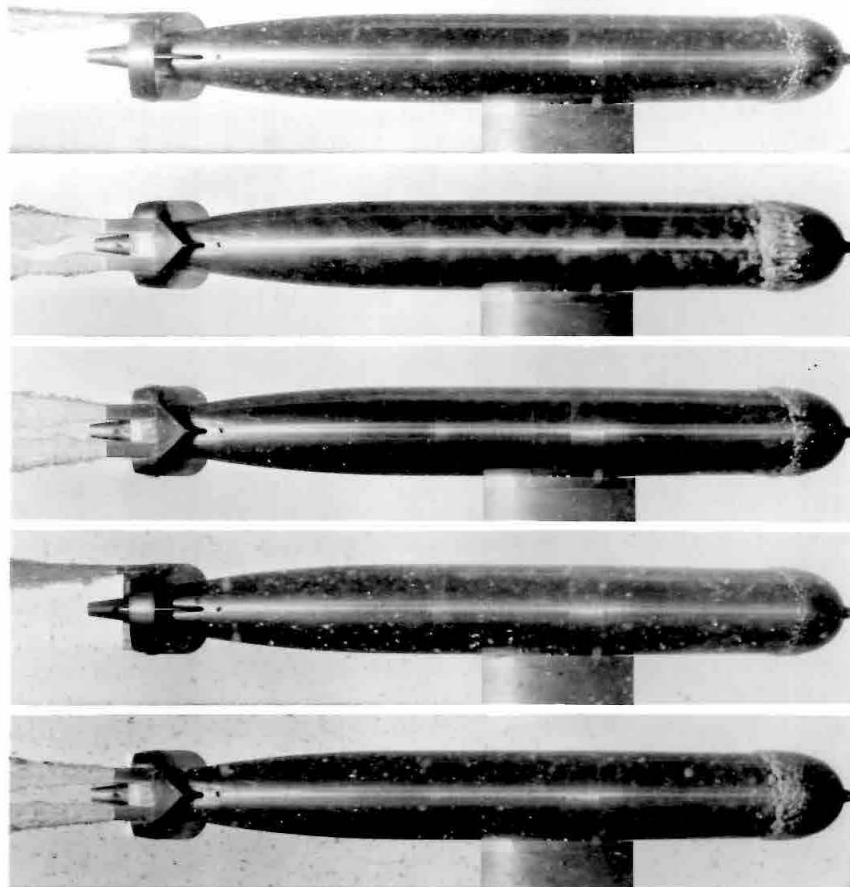
With the exhaust pipes reduced in length to only 0.75" beyond the rudder, as shown in photographs (d) and (e), Figure 5, there is still no tendency for the exhaust cavities to unite or spread to the rudder or ring. These pictures are for  $-6^\circ$  yaw and  $-3^\circ$  pitch, and although no picture is available for  $-6^\circ$  pitch, the observed result was the same as shown in photograph (e).

This series was concluded with the exhaust pipes cut flush with the trailing edge of the vertical rudder. In Figure 6, photographs (a), (b), and (d), it is seen that the exhaust causes no interference with the rudders for values of  $K$  of approximately 0.50, about 100% exhaust,  $-6^\circ$  yaw and pitch angles of  $-3^\circ$  and  $+6^\circ$ . At a pitch angle of  $-6^\circ$  and  $K$  of 0.51, shown in (c), the two exhaust cavities have united and have spread along the ring. It was also observed from the top of the model that the exhaust had enveloped the vertical rudder.

As just noted, the double exhaust pipe cut flush with the trailing edge of the vertical rudder would cause severe interference with the rudders, and probably the propellers, if operating at a  $K$  of 0.50 and  $-6^\circ$  pitch angle. It was observed that at  $K = 0.60$  and a pitch angle of  $-6^\circ$ , the exhaust gas cavities were regular and showed no tendency to spread, there being only slight cavitation around the rudder.

\*This torpedo operates at 40.5 knots and 15 feet submergence, corresponding to a value of the cavitation parameter,  $K$ , of 0.67. As noted in the previous paragraph, there was only slight cavitation noticeable for a  $K$  of 0.60 and a  $-6^\circ$  pitch angle, so it is considered probable that at the normal value of  $K$ , 0.67, operation should be satisfactory, neglecting the effect of the propellers.





(a)  
 $K = 0.50$   
 $\psi = -6^\circ$   
 $Q = 78\%$   
 PIPE = 2.69"

(b)  
 $K = 0.51$   
 $\alpha = 0^\circ$   
 $Q = 87\%$   
 PIPE = 2.69"

(c)  
 $K = 0.50$   
 $\alpha = -6^\circ$   
 $Q = 78\%$   
 PIPE = 2.69"

(d)  
 $K = 0.53$   
 $\psi = -6^\circ$   
 $Q = 87\%$   
 PIPE = 0.75"

(e)  
 $K = 0.50$   
 $\alpha = -3^\circ$   
 $Q = 83\%$   
 PIPE = 0.75"

VERTICAL RUDDER SET AT  $10^\circ$  PORT  
 PIPE LENGTHS, 2.69" AND 0.75"  
 $Q =$  GAS DISCHARGE

FIG. 5 DISCHARGE FROM DOUBLE EXHAUST PIPE

POWER-DRIVEN PROPELLER WITH SINGLE PIPE

In order to investigate the effect of the propeller on the spreading of the exhaust cavity, a special model was built with a motor-driven propeller. With this model it was possible to study any interference with the propeller that might be caused by the exhaust. While the prototype is equipped with dual propellers, this first model had only one propeller as this greatly simplified the design and construction of the model. The propeller was, in general, operated at 12,000 rpm, which gave a relation between propeller tip speed and water velocity analagous to that of the prototype.

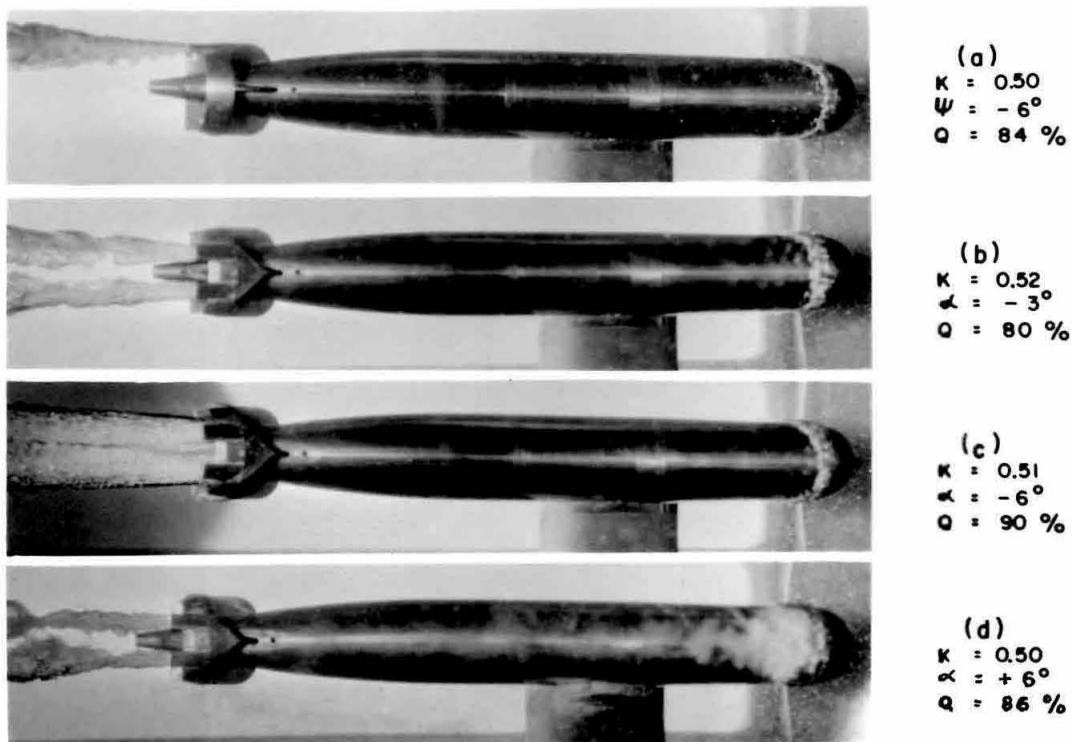
In all of these tests, the vertical rudder was set at  $10^\circ$  port. As before, the exhaust pipe length was measured aft from the trailing edge of the rudder. The tests were made only with a model with a single expanding exhaust pipe.

Photographs (a) and (b), in Figure 7, show an exhaust pipe length of 2.69" and a gas discharge of 75%. In (a) the pitch is  $-5^\circ$  with  $K = 0.44$ , and in (b) the yaw is  $+10^\circ$  with  $K = 0.49$ . No tendency for the exhaust cavity to spread along the rudder or into the propeller is discernible. It is, therefore, apparent that this 2.69" length of exhaust pipe would give satisfactory performance under normal operating conditions for all yaw angles up to  $10^\circ$  and all pitch angles less than  $-5^\circ$ .

Photographs (c), (d), and (e), in Figure 7, indicate performance with the exhaust pipe reduced to a length of 0.75". In the first two photographs, (c) and (d), the pitch angle was  $-3^\circ$  and  $K$  had the values of 0.65 and 0.47. At the higher value of  $K$ , there appears to be no interference with the rudder and propeller but when  $K$  is reduced to 0.47, the exhaust has spread down the entire length of the rudder and is touching the tips of the propeller blades. In photograph (e) of Figure 7, which was taken at a value of 0.65 for  $K$  and  $+10^\circ$  yaw, practically all of the rudder is enveloped in the exhaust. However, as will be pointed out later, this apparent interference with the rudder disappears when viewed from the opposite side. This length of exhaust pipe would be satisfactory, under normal conditions, only for very small pitch angles.

When the exhaust pipe is cut off flush with the trailing edge of the rudder, the exhaust causes much more serious interference with the rudder and propeller. The first three photographs in Figure 8 show the exhaust cavities for a discharge of 80% with pitch angles of  $0^\circ$ ,  $-3^\circ$ , and  $-5^\circ$ . In (a) for  $\alpha = 0$  and  $K = 0.69$ , there is some spreading of the exhaust down the rudder and this is greatly increased as shown in (b) and (c) for higher pitch angles and lower values of  $K$ .

Photographs (d) and (e), in Figure 8, are of especial interest as they show the discharge with the same value of  $K$  (0.66) and

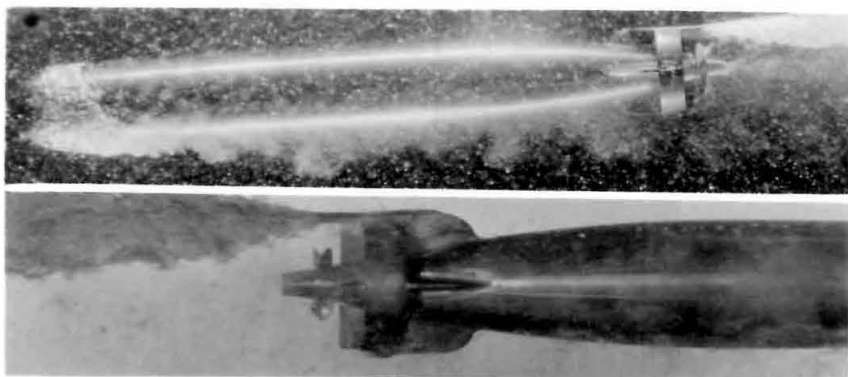


VERTICAL RUDDER SET AT  $10^\circ$  PORT  
 PIPE LENGTH = 0"  
 Q = GAS DISCHARGE

FIG. 6 DISCHARGE FROM DOUBLE EXHAUST PIPE

for  $+10^\circ$  and  $-10^\circ$  yaw. In (d),  $\psi = +10^\circ$ , the picture is taken looking at the outside of the exhaust cavity and the impression is gained that all of the rudder is enveloped as well as the tips of the propeller. Photograph (e), looking into the ring tail with a  $-10^\circ$  yaw, shows that the rudder and propeller are entirely free, and what appeared to be interference was caused by the exhaust cavity spreading along the ring. The true distribution of the exhaust cavity is observed when viewed from the opposite side, as shown in (d).

All of these observations indicate that there will be practically no interference with the propeller, the chief concern being to prevent interference with the action of the rudder. The 2.69" length of pipe is the shortest, of those tested, that would be certain to give satisfactory performance under normal operating conditions.

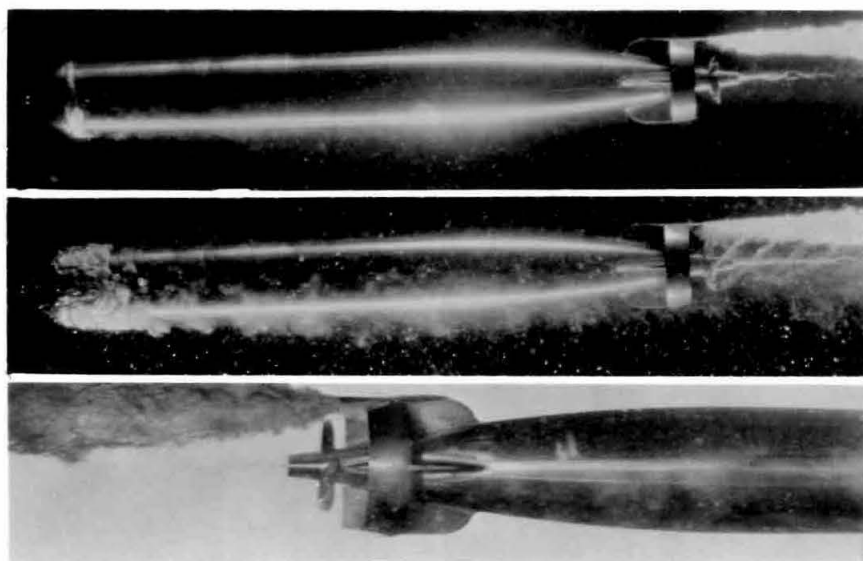


(a)  
 $K = 0.44$   
 $\alpha = -5^\circ$

(b)  
 $K = 0.49$   
 $\psi = +10^\circ$

$Q = 75\%$

PIPE = 2.69"



(c)  
 $K = 0.65$   
 $\alpha = -3^\circ$

(d)  
 $K = 0.47$   
 $\alpha = -3^\circ$

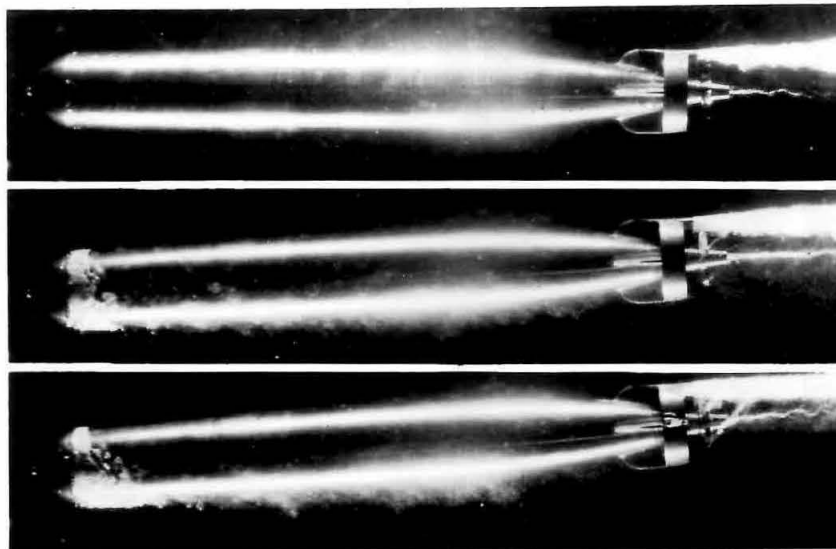
(e)  
 $K = 0.65$   
 $\psi = +10^\circ$

$Q = 75\%$

PIPE = 0.75"

VERTICAL RUDDER SET AT  $10^\circ$  PORT  
 $Q = \text{GAS}$  DISCHARGE

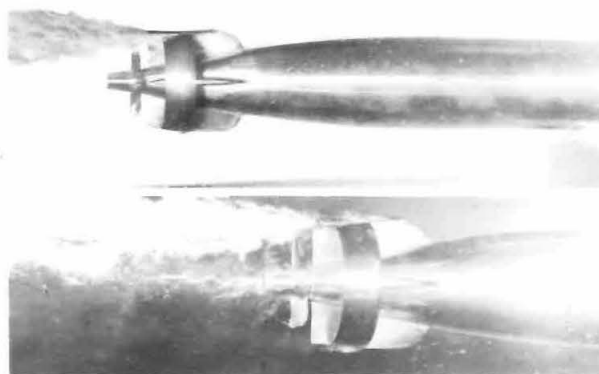
FIG. 7 DISCHARGE FROM SINGLE EXHAUST PIPE  
 WITH POWER-DRIVEN PROPELLER



(a)  
 $K = 0.69$   
 $\alpha = 0^\circ$

(b)  
 $K = 0.49$   
 $\alpha = -3^\circ$

(c)  
 $K = 0.48$   
 $\alpha = -5^\circ$



(d)  
 $K = 0.66$   
 $\psi = +10^\circ$

(e)  
 $K = 0.66$   
 $\psi = -10^\circ$

VERTICAL RUDDER SET AT  $10^\circ$  PORT  
 PIPE LENGTH = 0"  
 GAS DISCHARGE = 80 %

FIG. 8 DISCHARGE FROM SINGLE EXHAUST PIPE  
 WITH POWER-DRIVEN PROPELLER

CONCLUSIONS

The following conclusions, based on the results of these tests, seem to be justified:

1. A single expanding exhaust pipe will cause no interference with the rudders if it extends not less than  $3/4$ " aft of the trailing edge of the vertical rudder. This is for the projectile *without* propeller.

2. The performance of the double exhaust pipe discharging on both sides of the rudder is the same as for the single pipe. In order to avoid interference with the vertical rudder, the length of the pipes can be not less than  $3/4$ " from the trailing edge of the rudder.

3. The power-driven propeller tends to increase the interference of the exhaust gases with the rudders. To avoid interference with the vertical rudder, with the propeller in operation, a single exhaust pipe must extend at least 2.69" aft of the trailing edge of the rudder.

4. While the power-driven propeller with a single exhaust pipe, increased the interference of the exhaust with the vertical rudder, it was not observed that there was any tendency of the exhaust to be drawn into the propellers provided the exhaust pipe extended at least  $3/4$ " beyond the trailing edge of the rudder.



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## APPENDIX

### DEFINITIONS

#### YAW ANGLE, $\psi$

The angle, in a horizontal plane, which the axis of the projectile makes with the direction of motion. Looking down on the projectile, yaw angles in a clockwise direction are positive (+) and in a counterclockwise direction, negative (-).

#### PITCH ANGLE, $\alpha$

The angle, in a vertical plane, which the axis of the projectile makes with the direction of motion. Pitch angles are positive (+) when the nose is up and negative (-) when the nose is down.

#### LIFT, L

The force, in pounds, exerted on the projectile normal to the direction of motion and in a vertical plane. The lift is positive (+) when acting upward and negative (-) when acting downward.

#### CROSS FORCE, C

The force, in pounds, exerted on the projectile normal to the direction of motion and in a horizontal plane. The cross force is positive when acting in the same direction as the displacement of the projectile nose for a positive yaw angle, i.e., to an observer facing in the direction of travel, a positive cross force acts to the right.

#### DRAG, D

The force, in pounds, exerted on the projectile parallel with the direction of motion. The drag is positive when acting in a direction opposite to the direction of motion.

#### MOMENT, M

The torque, in foot pounds, tending to rotate the projectile about a transverse axis. Yawing moments tending to rotate the projectile in a clockwise direction (when looking down on the projectile) are positive (+), and those tending to cause counterclockwise rotation are negative (-). Pitching moments tending to rotate the projectile in a clockwise direction (when looking at the projectile from the port side) are positive (+), and those tending to cause counterclockwise rotation are negative (-).

In accordance with this sign convention a moment has a de-stabilizing effect when it has the same sign as the yaw angle or the opposite sign of the pitch angle.

In all model tests the moment is measured about the point of support. Moments about the center of gravity of the projectile have the symbol,  $M_{cg}$ .

#### NORMAL COMPONENT, N

The sum of the components of the drag and cross force acting normal to the axis of the projectile. The value of the normal component is given by the following:

$$N = D \sin \psi + C \cos \psi \quad (1)$$

in which

$N$  = Normal component in lbs

$D$  = Drag in lbs

$C$  = Cross force in lbs

$\psi$  = Yaw angle in degrees

#### CENTER OF PRESSURE, CP

The point in the axis of the projectile at which the resultant of all forces acting on the projectile is applied.

#### CENTER-OF-PRESSURE ECCENTRICITY, e

The distance between the center of pressure (CP) and the center of gravity (CG) expressed as a decimal fraction of the length (1) of the projectile. The center-of-pressure eccentricity is derived as follows:

$$e = (l_{cp} - l_{cg}) \frac{1}{l} = \frac{1}{l} \frac{M_{cg}}{N} \quad (2)$$

in which

$e$  = Center-of-pressure eccentricity

$l$  = Length of projectile in feet

$l_{cg}$  = Distance from nose of projectile to CG in feet

$l_{cp}$  = Distance from nose of projectile to CP in feet

# COEFFICIENTS

The three force and moment coefficients used are derived as follows:

$$\text{Drag coefficient, } C_D = \frac{D}{\rho \frac{V^2}{2} A_D} \quad (3)$$

$$\text{Cross force coefficient, } C_C = \frac{C}{\rho \frac{V^2}{2} A_D} \quad (4)$$

$$\text{Moment coefficient, } C_M = \frac{M}{\rho \frac{V^2}{2} A_D l} \quad (5)$$

in which

D = Measured drag force in lbs

C = Measured cross force in lbs

$\rho$  = Density of the fluid in slugs/cu ft =  $w/g$

w = Specific weight of the fluid in lbs/cu ft

g = Acceleration of gravity in ft/sec<sup>2</sup>

$A_D$  = Area in sq ft at the maximum cross section of the projectile taken normal to the geometric axis of the projectile

V = Mean relative velocity between the water and the projectile in ft/sec

M = Moment, in foot-pounds, measured about any particular point on the geometric axis of the projectile

l = Overall length of the projectile in feet

## CONTROL ANGLE

In considering the effect of rudders on static stability, either in yaw or pitch, the term "control angle" is used to denote the yaw below which a given rudder setting with opposite sign to the yaw will tend to return the projectile to zero yaw, and above which the yaw will further increase. The control angle is useful for indicating the effectiveness of rudders and for comparing the static stability of different projectiles with equal rudder settings.

RUDDER EFFECT

The total increase or decrease in moment coefficient, at a given yaw or pitch angle, resulting from a given rudder setting. This increase or decrease in moment coefficient is measured from the moment coefficient curve for neutral rudder setting.

REYNOLDS NUMBER

In comparing hydraulic systems involving only friction and inertia forces, a factor called Reynolds number is of great utility. This is defined as follows:

$$R = \frac{lV}{\nu} = \frac{lV\rho}{\mu} \quad (6)$$

in which

R = Reynolds number

l = Overall length of projectile, feet

V = Velocity of projectile, feet per sec

$\nu$  = Kinematic viscosity of the fluid, sq ft per sec =  $\mu/\rho$

$\rho$  = Mass density of the fluid in slugs per cu ft

$\mu$  = Absolute viscosity in pound-seconds per sq ft

Two geometrically similar systems are also dynamically similar when they have the same value of Reynolds number. For the same fluid in both cases, a model with small linear dimensions must be used with correspondingly large velocities. It is also possible to compare two cases with widely differing fluids provided l and V are properly chosen to give the same value of R.

CAVITATION PARAMETER

In the analysis of cavitation phenomena, the cavitation parameter has been found very useful. This is defined as follows:

$$K = \frac{p_L - p_B}{\rho \frac{V^2}{2}} \quad (7)$$

in which

K = Cavitation parameter

$p_L$  = Absolute pressure in the undisturbed liquid, lbs/sq ft

$p_B$  = Vapor pressure corresponding to the water temperature, lbs/sq ft

V = Velocity of the projectile, ft/sec

$\rho$  = mass density of the fluid in slugs per cu ft =  $w/g$

$w$  = weight of the fluid in lbs per cu ft

$g$  = acceleration of gravity

Note that any homogeneous set of units can be used in the computation of this parameter. Thus, it is often convenient to express this parameter in terms of the head, i.e.,

$$K = \frac{h_L - h_B}{\frac{\bar{v}^2}{2g}} \quad (8)$$

where

$h_L$  = Submergence plus the barometric head, ft of water

$h_B$  = Pressure in the bubble, ft of water

It will be seen that the numerator of both expressions is simply the net pressure acting to collapse the cavity or bubble. The denominator is the velocity pressure. Since the entire variation in pressure around the moving body is a result of the velocity, it may be considered that the velocity head is a measure of the pressure available to open up a cavitation void. From this point of view, the cavitation parameter is simply the ratio of the pressure available to collapse the bubble to the pressure available to open it. If the  $K$  for incipient cavitation is considered, it can be interpreted to mean the maximum reduction in pressure on the surface of the body measured in terms of the velocity head. Thus, if a body starts to cavitate at the cavitation parameter of one, it means that the lowest pressure at any point on the body is one velocity head below that of the undisturbed fluid.

The shape and size of the cavitation bubbles for a specific projectile are functions of the cavitation parameter. If  $p_B$  is taken to represent the gas pressure within the bubble instead of the vapor pressure of the water, as in normal investigations, the value of  $K$  obtained by the above formula will be applicable to an air bubble. In other words, the behavior of the bubble will be the same whether the bubble is due to cavitation, the injection of exhaust gas, or the entrainment of air at the time of launching.

The following chart gives values of the cavitation parameter as a function of velocity and submergence in sea water.

#### GENERAL DISCUSSION OF STATIC STABILITY

Water tunnel tests are made under steady flow conditions, consequently the results only indicate the tendency of the steady state hydrodynamic couples and forces to cause the projectile to return to or move away from its equilibrium position after a

disturbance. Dynamic couples and forces including either positive or negative damping are not obtained. If the hydrodynamic moments are restoring the projectile, then it is said to be statically stable, if nonrestoring, statically unstable. In the discussion of static stability the actual motion following a perturbation is not considered at all. In fact, the projectile may oscillate continuously about an equilibrium position without remaining in it. In this case it would be statically stable but would have zero damping and hence, be dynamically unstable. With negative damping a projectile would oscillate with continually increasing amplitude following an initial perturbation even though it were statically stable. Equilibrium is obtained if the sum of the hydrodynamic, buoyant, and propulsive moments equal zero. In general, propulsive thrusts act through the center of gravity of the projectile so only the first two items are important.

If a projectile is rotating from its equilibrium position so as to increase its yaw angle positively, the moment coefficient must increase negatively (according to the sign convention adopted) in order that it be statically stable. Therefore, for projectiles without controls or with fixed control surfaces, a negative slope of the curve of moment coefficient vs yaw gives static stability and a positive slope gives instability. For a projectile without controls, static stability is necessary for a successful flight unless stability is obtained by spinning as in the case of rifle shells. For a projectile with controls, stabilizing moments can be obtained by adjusting the control surfaces, and the slope of the moment coefficient, as obtained with fixed rudder position, need not give static stability. Where buoyancy either acts at the center of gravity or can be neglected, equilibrium is obtained when the hydrodynamic moment coefficient equals zero. For symmetrical projectiles this occurs at zero yaw angle, i.e., when the projectile axis is parallel to the trajectory. For nonsymmetrical projectiles, such as a torpedo when the rudders are not neutral, the moment is not zero at zero yaw but vanishes at some definite angle of attack. Where buoyancy cannot be neglected equilibrium is obtained when  $C_M = -C_{Buoyancy}$  and the axis of the projectile is at some angle with the trajectory.

For symmetrical projectiles the degree of stability or instability can be obtained from the center-of-pressure curves. If the center of pressure falls behind the center of gravity, a restoring moment exists giving static stability. If the center of pressure falls ahead of the center of gravity, the moment is nonrestoring, and the projectile will be statically unstable. The degree of stability or instability is indicated approximately by the distance between the center of gravity and the center of pressure. In general, for nonsymmetrical projectiles, the cross force or lift is not zero when the moment vanishes so that the center of pressure curve is not symmetrical and the simple rules just stated cannot be used to determine whether or not the projectile will be stable. In such cases careful interpretation of the moment curves is a more satisfactory method of determining stability relationship.



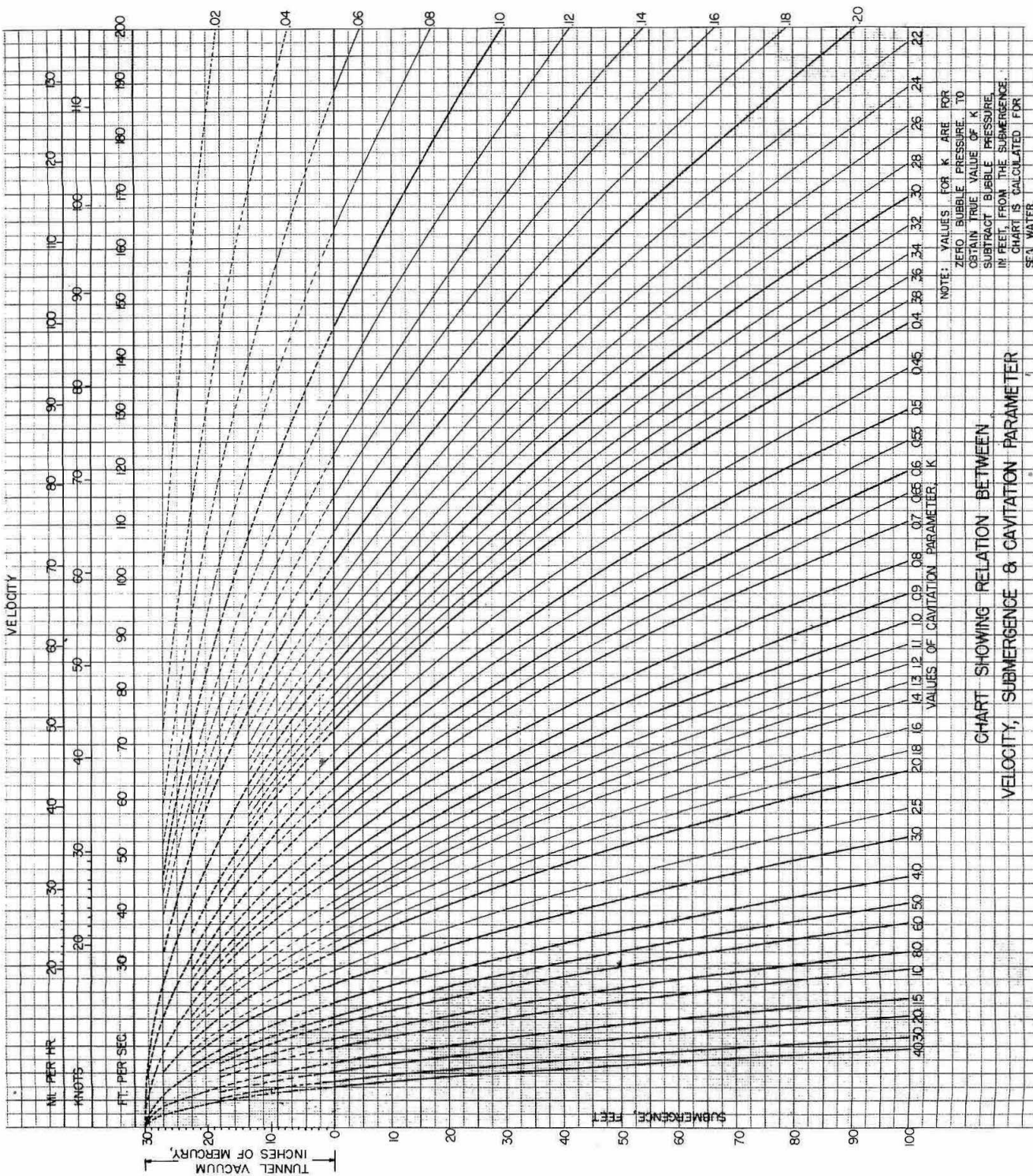


CHART SHOWING RELATION BETWEEN  
VELOCITY, SUBMERGENCE & CAVITATION PARAMETER